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Suprathermal Electrons and Peak Magnetic Fields in Laser Target-Plasmas

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The contribution of suprathermal electrons to the magnetic field generated in laser-target plasmas is discussed in terms of a two-fluid model including a single-temperature suprathermal electron fluid. In the neighborhood of the critical depth, one can approximate the effect of suprathermal electrons on the peak magnetic field by a simple multiplying factor on the source term due to the thermal electrons.

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SUPRATHERMAL ELECTRONS AND PEAK MAGNETIC FIELDS IN LASER TARGET-PLASMAS

Both suprathermal electrons[1] and self-generated magnetic fields[2] have been invoked independently to explain hard X-ray spectra produced in laser target interaction experiments. In this paper, we show that suprathermal electrons tend to reduce self-generated magnetic fields in the region of the critical depth where they reach their peak values. From our model and the experimentally observed magnetic fields, we can infer an upper limit on the density of suprathermal electrons for a given suprathermal electron temperature.

Because of their larger conductivity, the suprathermal electrons tend to carry a large fraction of the total electron current. However, since they have longer mean free paths, the suprathermal electron gradients (both in density and temperature) are smaller than the thermal gradients near the critical depth, and as a result, the magnetic field sources they generate are smaller in that region.

The model used to describe these fields is a two-fluid model consisting of thermal plasma and a single-temperature suprathermal electron fluid. This formulation includes both the contributions of suprathermal electron currents to the magnetic field sources, and also the influence of magnetic fields on transport of energetic electrons produced in the vicinity of the critical surface. Microturbulence effects[3] are not included. In the neighborhood of the critical depth the magnetic equation simplifies further, and analytic and numerical solutions are presented for that case.

In our self-consistent approach, both thermal and suprathermal electrons experience the same electric field. This field can be expressed by writing the generalized Ohm's law for each electron species,

$$\underset{\sim}{E} = -\frac{1}{c}\underset{\sim}{V} \times \underset{\sim}{B} - \frac{1}{eN_s}\nabla \underset{\sim}{P}_s + \frac{\underset{\sim}{R}_s}{eN_s} + \frac{1}{ecN_s}\underset{\sim}{J}_s \times \underset{\sim}{B} + \frac{\underset{\sim}{J}_s}{\sigma_s} \qquad (1)$$

Note: Manuscript submitted May 13, 1977.

$$\underset{\sim}{E} = -\frac{1}{c}\underset{\sim}{V} \times \underset{\sim}{B} - \frac{1}{eN_t}\nabla \underset{\sim}{P}_t + \frac{\underset{\sim}{R}_t}{eN_t} + \frac{1}{ecN_t}\underset{\sim}{J}_t \times \underset{\sim}{B} + \frac{\underset{\sim}{J}_t}{\sigma_t} , \tag{2}$$

where the index t refers to thermal and s to suprathermal electrons, and collisions between suprathermal and thermal electrons have been neglected. Axi-symmetry has been assumed and we have used Braginskii's notation[4]. Neglecting the $\underset{\sim}{J} \times \underset{\sim}{B}$ terms (or $B^2/8\pi NkT$), setting $\sigma = \sigma_s + \sigma_t$ and noting that

$$\underset{\sim}{E} = \frac{\sigma_s}{\sigma}\underset{\sim}{E} + \frac{\sigma_t}{\sigma}\underset{\sim}{E} , \tag{3}$$

Eqs. (1) and (2) can be written as

$$\underset{\sim}{E} = -\frac{1}{c}\underset{\sim}{V} \times \underset{\sim}{B} - \frac{\sigma_s}{\sigma}\frac{1}{eN_s}\nabla \underset{\sim}{P}_s + \frac{\sigma_s}{\sigma}\frac{\underset{\sim}{R}_s}{eN_s}$$

$$-\frac{\sigma_t}{\sigma}\frac{1}{eN_t}\nabla \underset{\sim}{P}_t + \frac{\sigma_t}{\sigma}\frac{\underset{\sim}{R}_t}{eN_t} + \frac{1}{\sigma}(\underset{\sim}{J}_s + \underset{\sim}{J}_t) . \tag{4}$$

Using Ampère's law allows us to eliminate the currents and the equation for the B-field becomes

$$\frac{\partial \underset{\sim}{B}}{\partial t} = \underset{\sim}{\nabla} \times (\underset{\sim}{V} \times \underset{\sim}{B}) - \frac{c^2}{4\pi}\underset{\sim}{\nabla} \times \left(\frac{1}{\sigma}\underset{\sim}{\nabla} \times \underset{\sim}{B}\right)$$

$$+ \frac{c}{e}\underset{\sim}{\nabla} \times \left[\frac{\sigma_t}{\sigma}\frac{1}{N_t}\underset{\sim}{\nabla}(N_t T_t)\right] + \frac{c}{e}\underset{\sim}{\nabla} \times \left[\frac{\sigma_s}{\sigma}\frac{1}{N_s}\underset{\sim}{\nabla}(N_s T_s)\right]$$

$$- \frac{c}{e}\underset{\sim}{\nabla} \times \left[\frac{\sigma_s}{\sigma}\frac{\underset{\sim}{R}_s}{N_s}\right] - \frac{c}{e}\underset{\sim}{\nabla} \times \left[\frac{\sigma_t}{\sigma}\frac{\underset{\sim}{R}_t}{N_t}\right] . \tag{5}$$

The source on the right side of Eq.(5) (which involves two conductivities) agrees with that from a single fluid model (based on a single temperature) for early times $t \rightarrow 0$, but differs for finite times.

We now assume that T_s is homogeneous, which is reasonable due to the relatively large energy relaxation time of the suprathermal electrons[5]. The electrical conductivities are also proportional to

$$\sigma_t \sim (N_t/N_i)T_t^{3/2} \ , \quad \sigma_s \sim (N_s/N_i)T_s^{3/2} \ ,$$ neglecting the weaker $\ln\Lambda$ dependence. The ratio σ_t/σ can then be written as

$$\frac{\sigma_t}{\sigma} = \frac{T_t^{3/2}}{\alpha T_s^{3/2} + T_t^{3/2}} \tag{6}$$

with $\alpha = N_s/N_t$. After some algebra, but keeping all terms, Eq. (5) becomes

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{V} \times \mathbf{B}) - \frac{c^2}{4\pi} \nabla \times \left(\frac{1}{\sigma} \nabla \times \mathbf{B}\right)$$

$$+ \frac{c}{eN_t}\left\{\frac{1.5\ \alpha r^{3/2} + 1}{(\alpha r^{3/2} + 1)^2}\right\} \nabla T_t \times \nabla N_t - \frac{cT_t}{eN_t^2}\left\{\frac{r^{3/2}(r - 1)}{(\alpha r^{3/2} + 1)^2}\right\} \nabla N_t \times \nabla N_s$$

$$+ \frac{c}{eN_t}\left\{\frac{r^{3/2}(1 - 1.5r)}{(\alpha r^{3/2} + 1)^2}\right\} \nabla T_t \times \nabla N_s - \frac{c}{e} \nabla \times \left\{\frac{1}{(\alpha r^{3/2} + 1)} \frac{\mathbf{R}_t}{N_t}\right\} \tag{7}$$

where $r = T_s/T_t$. The suprathermal force term $\mathbf{R}_s$, has vanished since there is no T_s gradient.

In general, in order to solve for $\mathbf{B}$, N_s needs to be known. Transport of the suprathermal electrons can be described for example by the following equations:

$$\frac{\partial N_s}{\partial t} + \nabla \cdot (N_s \mathbf{V}_s) = S - \frac{N_s}{\tau_s} \ , \tag{8}$$

where S is a source term located in the vicinity of the critical surface and N_s/τ_s is a sink term accounting for the energy loss of suprathermals through Coulomb collisions, and

$$\underset{\sim}{V}_s = -\frac{\sigma_s}{eN_s}\left[\frac{\sigma_t}{\sigma}\left(\frac{T_s}{N_s}\nabla \underset{\sim}{N}_s - \frac{1}{eN_t}\underset{\sim}{\nabla}\left(N_t T_t\right)\right) + \frac{\sigma_t}{\sigma}\,\frac{\underset{\sim}{R}_t}{eN_t} + \frac{c}{4\pi\sigma}\underset{\sim}{\nabla} \times \underset{\sim}{B}\right]$$

$$+ \frac{N_i}{N_s}\underset{\sim}{V} \quad , \tag{9}$$

using the generalized Ohm's law. No equation for T_s is needed since in this model T_s has been assumed homogeneous.

A simple special case can be considered for Eqs.(7)-(9), namely the field behavior near the critical depth. In this region we can assume N_s to be approximately homogeneous, since the mean free path of the suprathermal electrons is much larger than that of the thermal electrons. This approximation breaks down away from the critical depth.
Under these conditions, Eqs. (7) - (9) reduce to

$$\frac{\partial \underset{\sim}{B}}{\partial t} = \underset{\sim}{\nabla} \times (\underset{\sim}{V} \times \underset{\sim}{B}) - \frac{c^2}{4\pi}\underset{\sim}{\nabla} \times \left(\frac{1}{\sigma}\underset{\sim}{\nabla} \times \underset{\sim}{B}\right)$$

$$- \frac{c}{eN_t}\nabla \underset{\sim}{N}_t \times \nabla \underset{\sim}{T}_t \left\{\frac{\frac{3}{2}\,\alpha r^{3/2} + 1}{(\alpha r^{3/2} + 1)^2}\right\} - \frac{c}{e}\underset{\sim}{\nabla} \times \left\{\frac{1}{(\alpha r^{3/2}+1)}\quad\frac{\underset{\sim}{R}_t}{N_t}\right\}, \tag{10}$$

This single equation still carries quantitative information about a single-temperature suprathermal electron fluid. The factor modifying the classical magnetic field source term (representing the contribution of the suprathermal electrons) has been plotted in Fig. 1 as a function of r for different values of α. A restrictive condition (namely $\alpha r \leqslant 1$ which corresponds to $N_s T_s \leqslant N_t T_t$) has been imposed on the separate variations of α and r. The magnitude of the thermal force term decreases rapidly as r increases and for cases of practical interest, we note that the classical magnetic field source term is reduced to about 1/3 of its value.

Complete results including the thermal force terms have been obtained numerically and are shown in Fig. 2. The maximum B-field obtained in the laser target interaction described in detail in reference 6 has been plotted as a function of time. Note that in these calculations α is kept constant but r is not since T_s is constant but $T_t = T_t(x,t)$. The case $\alpha = 0$ corresponds to no suprathermal electrons. The three other curves on the figure show the separate influence of α and T_s , keeping the other parameter constant. For fixed α , increasing T_s diminishes the strength of the B-field. This result appeared already in Fig. 1 and follows from the fact that the suprathermal electrons carry a larger fraction of the total current as their temperature increases. For fixed T_s , the variation with α follows that one already displayed in Fig. 1 for the same reason indicated above.

In summary, we have shown, within the framework of our model, that the peak magnetic field near the critical depth is reduced by the presence of suprathermal electrons. This result can also be obtained by including a constant N_s in a simple analytic model for the critical depth fields[9]. If megaGauss fields are indeed present in laser target experiments[7,8], one can conclude that the electron suprathermal population is both small compared to the thermal one, and has a temperature which is not much larger than that deduced from thermal flux-limit arguments(i.e., by equating the laser deposition power with the thermal flux from the deposition volume). The full problem of solving for the magnetic field in regions away from the critical depth involves solving the full system of Eqs.(7)-(9) and will be adressed in later work.

REFERENCES

1. V.W. Slivinsky, H.N. Kornblum, H.D. Shay, J. Appl. Phys. 46, 1973 (1975).
2. B.H. Ripin et al., Phys. Rev. Lett. 34, 1313 (1975).
3. W.M. Manheimer, Phys. Fluids (in press, 1976).
4. S.I. Braginskii, in Reviews of Plasma Physics, ed. by M.A. Leontovich (Consultants Bureau, New York, 1965), p. 205.
5. L. Spitzer, Physics of Fully Ionized Gases, 2nd edition, 1962, Wiley, New York.
6. D.G. Colombant and N.K. Winsor, submitted to Phys. Rev. Lett. (1976).
7. J.A. Stamper and B.H. Ripin, Phys. Rev. Lett. 34, 138 (1975).
8. M.G. Drouet and R. Bolton, Phys. Rev. Lett. 36, 591 (1976).
9. D.A. Tidman and L.L. Burton, Phys. Rev. Lett. 37, 1397 (1976).

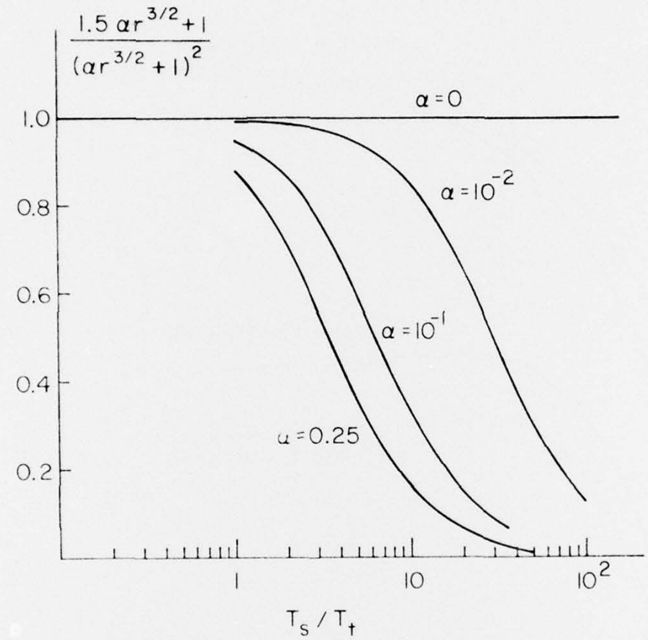

Fig. 1 — Suprathermal electron correction in the classical magnetic field source term as a function of T_s/T_t for various values of $\alpha = N_s/N_t$

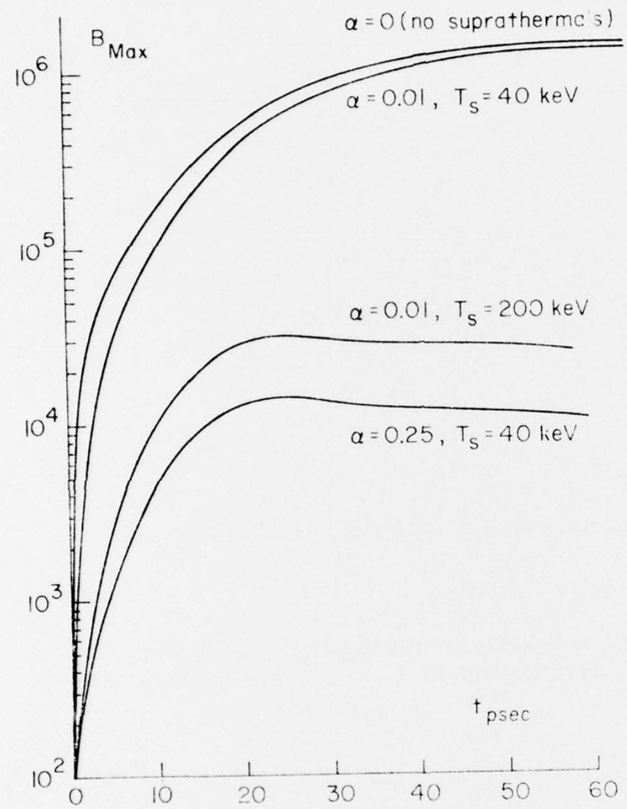

Fig. 2 — Maximum B-field in Gauss as a function of time for various values of α and T_s for the laser target interaction described in Ref. 6